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The Far-Reaching Effects of Quaternary Sealevel Changes on the Flat Continent of Australia

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ABSTRACT: Major changes of sealevel have resulted from changes in the world ice budget. Australia even in the Ice Age had little ice, but of course is affected by the global eustatic changes. Indeed, it has been affected more by reason of being the flattest of the six continents.

Trees in position of growth under the sea, freshwater peats, relict sediments and buried channels on the continental shelf bear witness to changes of sealevel. The stratigraphy and chronology of the Yarra Delta, Victoria, are used to illustrate this. Eustasy in relation to tectonics, ecology and sedimentation is discussed.

INTRODUCTION

So ingrained is the concept of the last Ice Age in the literature of a number of scientific disciplines that the knowledge of this major world event seems to have been with us always. However, it is only about 130 years ago (Darwin 1887, 1: 250) that the idea was first put forward as a scientific proposition. Such was the magnitude of this new concept, and so far-reaching its implications, that some eminent scientists of the day could not accept it. Darwin did, but Elie de Beaumont did not. The sediment of present rivers was then called the Alluvium, while the 'superficial drift' of the Ice Age was named the Diluvium.

It was soon realized that one of the major effects of the Ice Age was drastically to alter sealevel, thus changing the shape and extent of continents, creating land bridges across which plants and animals could migrate, altering by climatic change the distributions of soils, plants and animals (including man) across the world, turning estuaries into valleys, and continental shelves into extensive coastal plains. We are still in the Ice Age; we live in an Interglacial. Thus, although the sea has been higher than at present, most of the range of sealevel change lies below the present level.

Modern man is an Ice Age animal, adjusted to the exigencies of this unusual Era. The older genera of men such as *Australopithecus* go back into the late Tertiary, but *Homo* is an Ice Age genus, albeit first evolved in the warm continent of Africa. All men now belong to the one species, which we have called *Homo sapiens*. This is not a boast, but a reference to the fact that man alone is self-conscious and a thinker. Sir Julian Huxley (1957) was so impressed with the significance of this that he made man a separate Kingdom, the Psychozoa.

WORLD ICE BUDGET AND SEALEVELS

Ice was of course the characteristic product of the Ice Age. What amazed the first discoverers of the Ice Age was that great glaciers and ice caps had extended down over Europe and North America, so that many prosperous countries would then have been but huge ice fields. It was not realized at first that the fertility of those countries arose from the fact that the ice lobes and glaciers, like giant bulldozers, had swept away the older leached soils, allowing their replacement by young, rich soils.

In due time the existing volume of ice was calculated, and the amount of ice generated in the last stage of the Ice Age estimated. When the great ice caps melted, the water ran into the sea, and so sealevel rose. Thus there was developed the idea of the ice budget, i.e., the mutual relationships of world ice volume and seawater volume. A great deal of water is carried in the atmosphere, but calculations show that this factor can be neglected, because the condensation of all water

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from the atmosphere (an extreme that would never happen) would raise sealevel only 3·7 cm. Indeed nearly all the water on this planet (97·6%) is in the oceans. Although only 1·7% of this is contained in existing ice, the melting of this ice would raise sealevel enough to drown London, New York, Melbourne and hundreds of other cities.

The changes of sealevel brought about by changes in the ice budget are called eustatic, or more precisely glacio-eustatic; the principle involved is called eustasy (Gill in Fairbridge 1968). Until the 1950s there were many doubts about glacio-eustasy, e.g.

1. Were the advances of the glaciers (increase of ice volume) and the lowering of sealevel really synchronous?
2. Were the glaciations in the northern and southern hemispheres synchronous, or did they alternate?

Such alternation would of course affect the degree of sealevel change. These were problems of chronology, and the means to solve them became available in 1950 with radiocarbon dating. The results have dispelled all doubts. As the glaciers advanced, sealevel rose. The effects were global. Apart from relatively small local effects such as would be expected, the whole system is synchronous throughout the world. These processes are still active, but over the past 6,000 years on a subdued scale (Fairbridge 1961).

Another problem arising from the study of the ice budget concerned the role of the Antarctic ice cap, since the volume of ice on Antarctica was unknown. During the International Geophysical Year work to determine this was initiated, and now a number of bores has been sunk through the ice, and a number of geophysical traverses have been run. For the first time, reasonable estimates of present and past volumes of ice in Antarctica have become possible. Professor R. F. Flint (in press) of Yale University has recalculated the world ice budget, including Antarctica, and the results are as interesting as they are surprising. There are many assumptions in such calculations, but they are at such a stage that they appear to be of the correct order. Professor Flint considers his results are minimal quantities. His figures show that 89% of the world's present ice is in the Antarctic Continent, and most of the remainder in Greenland. If the world's ice were melted, the volume of water resulting would be $24 \times 10^6 \times km^3$, the water volume being calculated as 92% of the ice volume. This amount of water would raise sealevel by 65 m. Calculation of the volume of Ice Age ice gives a minimal reduction of sealevel of 132 m apart from any isostatic effects. Geologic evidence from the sea floors suggest the sea dropped lower than this figure, supporting the conclusion that the figure is minimal.

It is thus clear that sealevel at the present time can be affected more by changes in the Antarctic ice cap than by changes in any other ice accumulation. This ice cap dominates the ice budget. Even if the calculations were out by as much as 20%, this would still be true. However, as climatic change affects the whole globe, large changes limited to Antarctica are not to be expected. The next largest ice mass is Greenland with 9·8% of the present ice volume. Antarctica and Greenland therefore possess (on present calculations) 99·1% of the world's ice, but the position was different in the Glacial Stages. Then the huge Scandinavian (17%) and North American (38%) ice sheets came into existence, and made up more than half of the world's ice volume (55%). The reason for so much ice remaining now on the Antarctic continent is its position as a land mass at the pole (in the northern hemisphere the Arctic Ocean occupies the polar region), and much of it consists of a high plateau. Thus the northern hemisphere ice sheets provided the majority of the water that lifted sealevel from the Last Glacial low to the present, viz. North America 38% of the Glacial Stage ice and Scandinavia 17%, making 55%. Antarctica provided 33%, making a total of 88%.

Even in the Ice Age Australia had little ice, because it is the flattest continent with no high mountains, and it is also the driest continent, with restricted precipitation. Nevertheless, the shorelines of Australia, like those of the rest of the world, were affected in a major way by the eustatic changes of sealevel. Indeed, they were more affected, because of the flatness of the continent (Fig. 1). If the Ice Age had been discovered first in Australia, it would have quite a different name because of the absence of ice. Perhaps it would have been called The Age of Changing Sealevels.

CONTINENTAL SHELF

Round all continents there is a submarine platform—the continental shelf. Indeed, it is more significant to think in terms of the continental terrace (the continental shelf plus the coastal plain) because the coastal flats are themselves in part a product of the higher sealevels. On this view, the outer edge of the continental shelf is the real border of the continent. Certainly, present sealevel has little significance in long term. It is ephemeral even from the point of view of the last 15,000 years. Until recent times man has looked on the mountains and the levels of the seas as

FIG. 1—Tasmania, the Australian mainland, and New Guinea, showing the connecting continental shelf that became land during low sealevels, permitting migrations of plants and animals (including man).

permanent, but neither are. The proved mobility of the land infers changing levels of the sea, quite apart from glacio-eustasy. However, the eustatic effects on sealevel are very rapid compared with the tectonic effects. Coastal geomorphology was long a problem until the present eustatic views were adopted. Features of both emergence and submergence were found on the same coasts.

During the time man has been on the earth, sealevel has been at or near the edge of the continental shelf a number of times, and also higher, covering the areas now occupied by coastal cities. However no human record has been retained of these things, because the changes have been masked by two factors: (1) the constantly changing level of the sea due to diurnal tides, and (2) the short life of a man compared with the time range of these changes.

The tides rise across the shore generally twice a day (or more precisely twice each lunar day) and erode the edge of the land, forming beaches and cutting shore platforms. With a very much longer frequency in the Quaternary (perhaps of the order of 50,000 years), the oceans have swept across the borders of the continents and back again, modifying the continental terraces by trimming the bedrock and distributing sediments. The major tool for performing this work is the powerful surf-zone. Its effectiveness is greatly increased because the transgressions and regressions of the sea are not smooth, but a series of oscillations. The surf-zone is like a rasp that is the more effective because rubbed to and fro across the surface it is abrading. Climatic changes are a complex of smaller cycles superimposed on larger ones, and since the ice-budget is presently the dominating factor in sealevel change, the complex variations in climate are reflected in complex oscillations of sealevel.

As would be expected, the outer edge of the continental shelf is not perfectly regular, but it occurs at a depth of about 200 m. Also, the shelf varies greatly in width. Thus in Australia it averages 22 km off the coast of N.S.W., but reaches 320 km on the NW. coast of the continent. The range of width of shelves round the world is 1-1,200 km. Because Australia is such a flat continent, the flooding of its terrace by the postglacial rise of sealevel is very extensive. Australia has the third largest area of continent shelf of all the countries of the world. During the Last Glacial, Australia had a land mass one-third larger than it is at present. At that time it had an extra 2,600,000 km^2. To the north, the Sahul Shelf was dry. There was no Torres Strait or Gulf of Carpentaria; most of the Arafura Sea was dry. New

Guinea was an extension of the mainland. Tasmania was a peninsula, and Kangaroo Island a promontory. The Great Barrier Reef area was a coastal plain. Likewise the islands and reefs along the W. coast were a coastal plain. To the NW. of the continent, the Sunda Shelf was dry, making Borneo, Indonesia, and the numerous smaller islands of that area a part of continental Asia. Crossings from Asia to Australia of many forms of life (including man) were greatly facilitated because the distance was shorter and the landfall more convenient. It is likely that the first migration of Aborigines to Australia occurred at such a time of low sealevel. The last low was 18-20,000 years ago, but good evidence is now available for Aboriginal occupation up to 32,000 y. BP, so they definitely crossed before the last low. The previous low level was about 60,000 y. BP, so that is a theoretical possibility for the time of first Aboriginal migration. This figure is twice the present demonstrable antiquity of the Australian Aborigines.

LEGISLATION ON THE CONTINENTAL SHELF

For a long time geologists have pointed out that the edge of the continental shelf is the real edge of the continent, that a number of times in the past this has been the actual shoreline, and that in this zone there occurs the transition from continental to oceanic crust. Interest is now shown in this concept by legislators because the shelf has become an economic issue. Oil has been discovered and exploited on many continental shelves of the world. The rivers entering the sea at the present coastline once ran right across the shelf and debouched at its margin. These rivers then carried gold, tin, rutile, diamonds, and other minerals useful to man to sites on the continental shelf. The powerful surf-zone of transgressive and regressive seas concentrated some of these minerals in ancient beach and shallow-water marine deposits. The technology is now available for their exploitation.

While not attempting to disturb the earlier concept of the high seas, or that of international air space, the United States has declared that it regards 'the natural resources of subsoil and the sea-bed of the continental shelf beneath the high seas but contiguous to the coasts of the United States as pertaining to the U.S., subject to its jurisdiction and control'. Similar declarations have been made by the Governor-General of Australia with respect to the continental shelves of Australia and New Guinea. Largely due to Australia's efforts, the definition of 'natural resources' has been extended to include certain living resources such as pearl shell, bêche-de-mer, and other 'organisms . . . on or under the seabed'. The study of the Australian continental shelf is now proceeding in order to discover what advantage can be taken of the deposits resulting from Quaternary changes of sealevel. However, the legal problems are complex (O'Connell 1970).

EVIDENCE THAT THE CONTINENTAL SHELF WAS DRY

1. *Trees in Position of Growth Below Sealevel.* Such have been reported in numerous places round the world, and for the present purpose some from SE. Australia will be cited. At Badger Head Bay in N. Tasmania (Edwards 1941) there are two bold headlands of hard rocks protecting a sandy beach nearly 6 km long. Three outcrops of peat and peaty sand protrude through the beach, and were examined by Mr. M. R. Banks and myself in 1958. The two outcrops in the middle of the bay contain in situ stumps of possibly tea-tree and *Banksia*. Specimens brought back for determination were too collapsed to permit certain identification. The stumps seen by us were below mean sealevel, and the tidal range was estimated at 2-2·5 m. Behind the beach is a sand ridge protected by a layer of storm-laid pebbles. Radiocarbon assay of stump wood gave an age of 7,380 ± 100 y. BP (N.Z.). Relative rise of sealevel has brought the beach up over the former swale deposit. No evidence could be found of tectonic movement in this region in the past 8,000 years, and stumps of this age are known in many places round the world on or near the shore, so the displacement is probably eustatic. A similar 'drowned forest' occurs at Port Sorrell (also on the N. coast of Tasmania), and on Cape Barren Island in Bass Strait.

When the Captain Cook Graving Dock in Sydney, N.S.W., was being excavated about 1940, the stump of a large tree was found in position of growth (Fig. 2) about 14·6 m below sealevel. Although it is not known for certain to what level of the fossil stump this depth was measured, those concerned think the depth was to the floor of the Dock as seen on the right side of Fig. 2. A piece of a large root about 15 cm in diameter was supplied for radiocarbon dating by Mr. C. L. Hoffmann of the Forestry Commission of N.S.W. Mr. H. D. Ingle of CSIRO Division of Forest Products determined the wood as probably *Eucalyptus gummifera* (bloodwood). As it would be useful to know the time of the death of the tree, thin slivers of wood were taken from the outside of the root as being the sample that would give a date nearest to this time. Dr. T. A. Rafter of the New Zealand Institute of Nuclear Sciences assayed

FIG. 2—Drawing by George Browning from a photograph taken during construction of the Captain Cook Dock, Sydney, N.S.W., showing a *Eucalyptus* stump in position of growth, with a drain cut below it. Radiocarbon age of outermost wood was 8360 y.

the sample, determining the age as 8,360 ± 110 y. BP. As the stump was in position of growth, it could not grow at that level unless it were out of contact with sea water. At the time of the death of the tree, the sea must therefore have been at least 3 m lower, viz. —18 m, because the tree was a large one. The wood of the root sample supplied is excellently preserved, and so must have been buried not a great time after the death of the tree. There is evidence that some decay took place in the sap-wood before the tree was submerged, but this is to be expected on the accepted rates of sealevel rise. The wood of the eucalypt tree in position of growth, 19 m below sealevel, at Spencer Street, Melbourne, is likewise very well preserved. The carpenters who worked it stated that it seemed no different from present-day timber except for a slight smell of hydrogen sulphide. The fairly common occurrence of tree stumps round the world from present sealevel down to about 30 m is a function of the rapid rise of sealevel during the Flandrian Transgression. Bores put down in Hobson Bay between Williamstown and the Gellibrand Light penetrated up to 4·3 m thickness of wood. This is interpreted as indicating a fossil forest buried beneath the sediments of the bay, and with some trunks still standing.

Etheridge, David and Grimshaw (1897) described a geological section of Shea's Canal, Sydney, N.S.W., that showed a fossil dugong about 1 m below LWL, and tree stumps just above and just below a disconformity 3 m below LWL (Fig. 3). Aboriginal stone axes were found approximately at the levels of the stumps.

In Melbourne, difficulty was experienced in building the Spencer Street bridge over the River Yarra in that, while on the N. bank there was a sound foundation of Pleistocene basalt, the S. abutment had to be built in deep late-Quaternary sediments of poor bearing-strength. As such estuarine sediments are notoriously variable, the engineers put down bores about every metre so that there would be no surprises. But there was a surprise in the form of a river red gum stump in position of growth 19·2 m below LWL. The bores

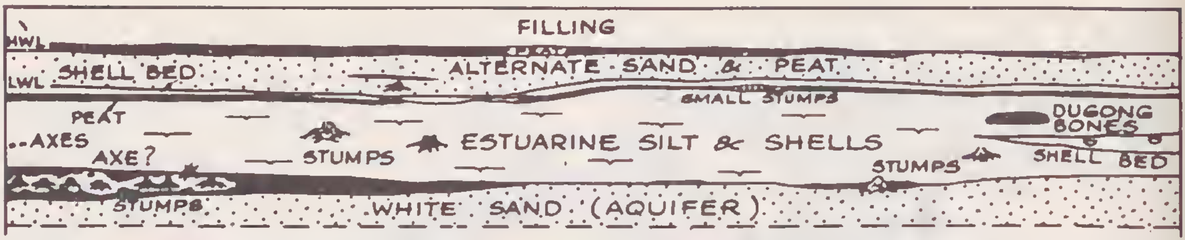

FIG. 3—Section of Sheas Creek Canal, Sydney, N.S.W., 6·6 m high and 660 m long (adapted from Etheridge *et al.*, 1897) showing Flandrian sediments with tree stumps below the present level of the sea.

had penetrated between the roots and missed the stump of the trunk, which was 1·2 m in diameter. The edge of the large cylinder used in emplacing Foundation No. 1 rested on the stump, which had to be removed.

As the stump was large, the tree had been growing there a long time. During that period at least, there could have been no salt water at the roots. As LWL is the datum on all the published plans of this bridge (Chapman 1929) it is presumed that the level given for the stump of '—63 ft' was measured therefrom; also as the work was held up by the cylinder resting on the top of the stump, and this is the only flat surface to which measurement could be made, it is assumed that the 19·2 m was measured to this level. If so, the position of the stump is as shown in Fig. 4, in a bed of peaty sediment accumulated on the swampy floor of this river channel. After the valley was cut, the river was diverted, otherwise such sediments could not accumulate. They continued to accumulate after the tree died, because the stump was covered by them. At 'the level of the stump' a layer of the moss *Sphagnum cristatum* was found, proving freshwater conditions, and suggesting a colder climate than at present since this moss now lives on the high plains. In this bed fossil pollen and the elytron of a beetle were found (Gill 1955). The diatoms recovered at this depth during the extension of the Breakwater Pier at Williamstown also indicate colder conditions. Such would be expected with sealevel as low as this. Radiocarbon dates of 8,300 and 8,700 years have been obtained for pieces of the stump, while the moss dated 8,330 years. The peaty bed in which the stump occurred is draped over the steep sides of the valley (Fig. 4) as well as over its floor, so the river flowed elsewhere. Evidence is given later that one course was under where the new Art Gallery is built, which accounts for the foundation difficulties experienced with that site.

2. *Freshwater Peats.* As such peats are the product of freshwater plants, their occurrence below sealevel is good evidence for changed relationships of land and sea. Peats are common under beaches and barriers, and in estuaries, while many have been discovered on the continental shelf. When the shelf is better known, reported occurrences will undoubtedly be more numerous. Submerged freshwater peat bogs off the coast of U.S.A. have been reported by Emery and Milliman (1971). They have been sampled to 68 m below the surface of the sea, and their radiocarbon dates extend to 15,000 years ago.

Fossil pollen from these peats show a succession from tundra, spruce, pine and oak, according to their degree of association with retreating glaciers (Emery *et al.* 1967). Other examples of non-marine peats now below sealevel are those described from the Netherlands by Jelgersma (1966), from Florida by Scholl and Stuiver (1967), from Bermuda by Neumann (pers. comm.), and from New Zealand by Suggate (1968).

3. *Relict Sediments.* Coral and algal reefs below the level at which they can now form, beach rock and shallow water shellbeds far out under the sea, widespread layers of sediment on the continental shelf out of context with present deposition, shallow water oolites under the deep sea, submerged sand ridges and aeolianite dunes, drowned archaeological sites, and the numerous teeth and bones of land animals found on the continental shelf are all evidence of the changed relationships of land and sea. Dill (1968) has recorded deeply submerged terraces and low sea cliffs on the continental slope of Southern California, Baja California, Mexico and Australia. Maxwell (1968) has described relict sediments on the Queensland continental shelf. Phipps and Shirley obtained shallow water marine shells from the outer continental shelf of N.S.W. at a depth of 128 m (70fm), which gave a radiocarbon date of 12,900 years (Gill 1967).

4. *Buried Channels.* The lowering of sealevel had a profound effect on the river systems of the world. As base level was so drastically and rapidly lowered, all the streams were rejuvenated. They cut down deeply into their channels and worldwide, except where the rocks were very soft,

carved river gorges. Conversely, when sealevel rose again, the channels so cut were infilled with soft sediments. Continuous seismic profiles have revealed some of these buried channels. One of the best known is the Hudson Channel off the NE. of North America. There is ample evidence that the same process occurred in Australia, but the channels have not been very closely studied as yet. However, some of these changes have been traced in the vicinity of major cities because they have resulted in major foundation problems during the construction of harbours, bridges, and heavy buildings. We will use the Yarra delta in Melbourne, Victoria, to illustrate the effects of the changes in sealevel.

THE YARRA DELTA

The present Yarra delta covers about 90 km². Its base is the kaolinized Tertiary Nillumbik Terrain of Silurian bedrock and Oligocene river sands and basalt, which has been flexed (Melbourne Warp) under Port Phillip Bay (Gill 1961, Bell *et al.* 1967). Two outcrops of Oligocene basalt (the South Melbourne hill, and a band from the River Yarra to Essendon) form a linear block oriented NW.-SE. fronting the Silurian ridge on which the central part of Melbourne is built (Fig. 5). This ancient basalt has been stripped off the Silurian ridge, and its present outcrop is actually the edge of a plate that continues under the delta, where it has been eroded during Quaternary low sealevels (Fig. 6). Bores through the basalt shown in Fig. 6 proved that there are two flows separated by carbonaceous sands. Pollen analysis by Dr. Isabel Cookson revealed taxa similar to those in the Altona and Yallourn brown coal, and hence the basalt is given an Oligocene age, but an older age is possible. Above the basalt there are four Quaternary formations (Fig. 7):

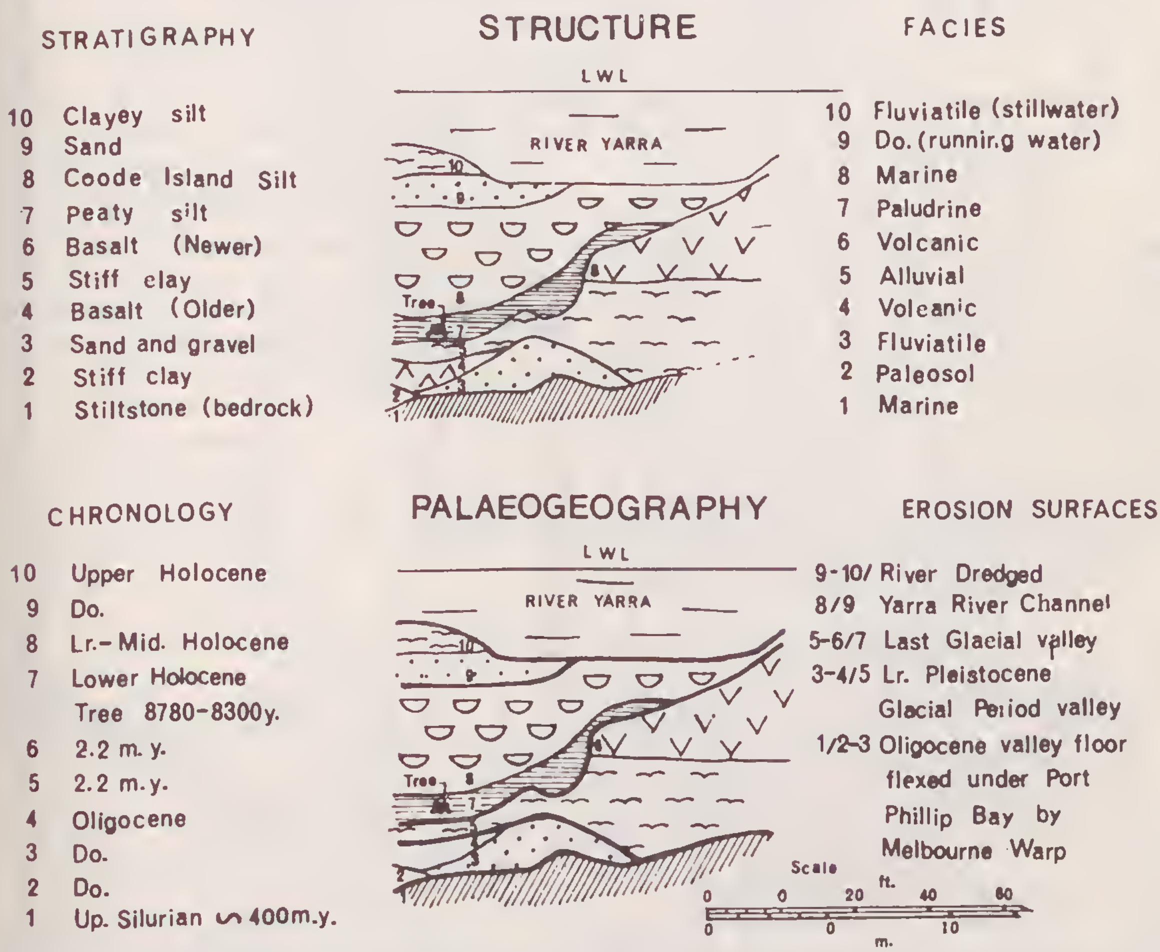

FIG. 4—Section of the S. abutment of the Spencer St. Bridge over the Yarra R., Melbourne, Victoria, showing a *Eucalyptus* stump *in situ* below present sealevel and covered by Flandrian sediments. The stratigraphy and chronology are summarized. Based on Chapman 1929.

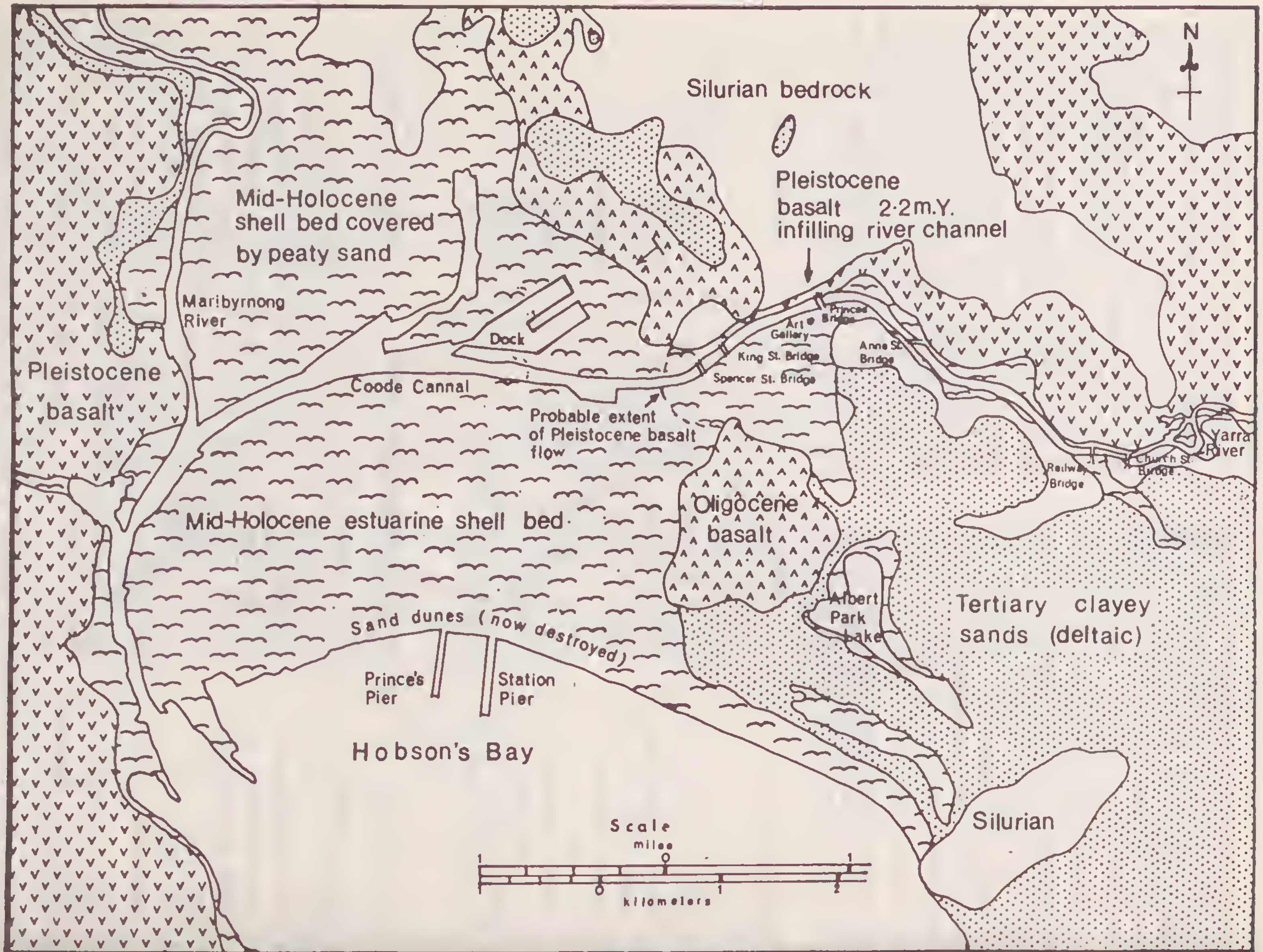

FIG. 5—Geological map of the Yarra R. Delta, Melbourne, Vic., showing the distribution of the formations, and the localities referred to in the text. Based on Geological Survey of Victoria map.

Port Melbourne Sand	*Holocene*
Coode Island Silt	*Holocene*
Fishermens Bend Silt	*Last Interglacial*
Moray Street Gravels	*Penultimate Glacial*

The two younger formations are dated by radiocarbon (Gill 1970), and the two older by interpretation of sealevel changes. In the bores sunk to test the foundations for the Lower Yarra Crossing (West Gate Bridge), this same stratigraphy is revealed. The section drawn from the bore logs shows the W. edge of the delta at Newport. Quaternary formations up to 46 m deep are emplaced in a valley excavated through the Lower Pleistocene basalt, and the underlying Tertiary fluviatile, marine, and marshland sediments. The two flows of Oligocene basalt shown in Fig. 6 are also present. See Aitchison and Lang 1962, Donald and Elwood 1962, Neilson and Jenkin 1967. The lowest Quaternary formation is the Moray Street Gravels (Neilson and Jenkin 1967).

In the course of the River Yarra this stratigraphy is complicated by the presence of a Lower Pleistocene basalt flow, or series of flows. The basalt is considered to be that dated in the Merri Creek as 2·2 m.y., but could be younger. The flow probably never extended beyond the valley between the two outcrops of Oligocene basalt (Fig. 5). It is underlain by alluvial clays (Fig. 4), and has been cut through by the rejuvenated Yarra River during low stands of the sea. The Yarra River flows at the interface between the basalt and the Silurian bedrock, where its course is strictly predetermined. Beyond this limit of the flow, however, the river has run in numerous channels across the 7 km wide fan of soft deltaic sediments. The present outlet of the river is hard against the edge of the Pleistocene lava field that defines the W. side of the delta. The shape of the course and its position are determined by the basalt. Thus the Oligocene and Pleistocene basalts have provided limits for delta formation, and river course positions.

The products of sealevel changes existing in the Yarra delta have profoundly affected certain aspects of the development of the city of Melbourne. To appreciate this, we need to look at the delta in its original condition. It was covered with vegetation, chiefly tea-tree (Bunce 1857). N. of the Yarra River and E. of the Maribyrnong River was a large shallow lake called 'Salt Lake' on Russell's original map of Melbourne, but later 'Batman's Swamp' (Selwyn 1868) and 'West Melbourne Swamp'. There were two 'lagoons', one in the area of the present Albert Park Lake, and the other at Port Melbourne where it obviously constituted the remnant of an old river channel. The first boats to sail up the Yarra had difficulty negotiating the sand bar at the mouth and the snags in the stream. They were forced to stop at the level of Market Street because there the Pleistocene basalt formed a bar across the river, making a waterfall about 1 m high. The pool below the bar was Melbourne's first port, but later landings were commonly made on Liardet's Beach (Port Melbourne), whence people walked two miles to the Yarra River which they crossed on a ferry. In time of flood, the Yarra waters flowed in a broad sheet across the flats to Port Melbourne in the vicinity of the lagoon. Further west there were sand ridges, and that is why Port Melbourne was at first called Sandridge. Similar sand ridges existed at Williamstown. The first bad flood occurred in October 1844. A particularly bad flood in December 1863 poured across South Melbourne to Port Melbourne for several days without inter-

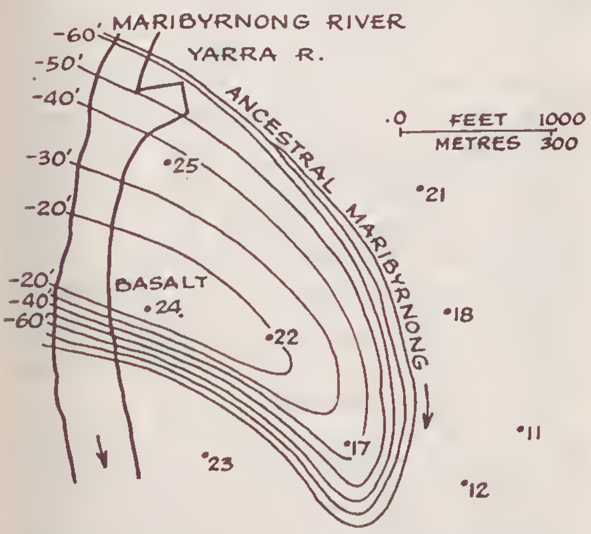

FIG. 6—Eroded basalt flow at Coode Island, Melbourne, buried in the Quaternary sediments of the Yarra Delta, and revealed by Melbourne Harbor Trust bores. Compare Figs. 7-8.

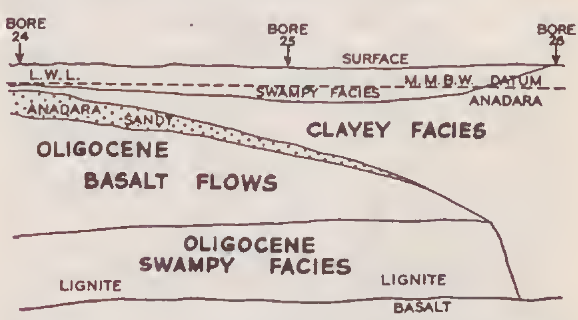

FIG. 7—Section at Coode Island, Melbourne, showing two Tertiary basalt flows covered by Flandrian sediments. Compare Figs. 6, 8.

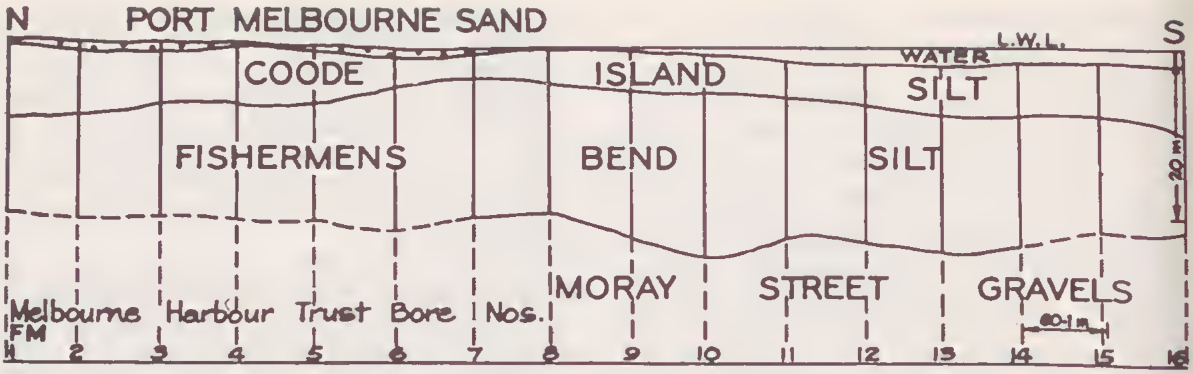

FIG. 8—Section based on cores from Melbourne Harbor Trust bores at Coode Island, Melbourne, examined by the author. Compare Figs. 6-7.

ruption (Adams 1865, Rawlinson 1865, Smith 1865, 1874). Flood control was decided upon, and in due time the river was straightened and deepened and the basalt bar across the Yarra removed.

As far as I can discover, the lagoon at Port Melbourne was used as a shelter for boats at first. Later a jetty was built in Hobson Bay just W. of the lagoon, and later a second one was built. This installation was gradually elaborated into the present Port Melbourne, but there have been difficulties as a result of sealevel changes. As heavier harbour installations were built, better foundations were necessary, but they could not be found at reasonable depth, because the port is built over an old course of the Yarra which, during a low level of the sea, cut to 30 m. The present piers are not based on this bedrock, but virtually float in the mud of this Ice Age channel. When more recently another dock was required, it was possible to choose a site with much better foundations, the River Entrance Dock. It was unfortunate that the first site chosen happened to be over a deep channel. The River Entrance Dock has a stratigraphy like that of Coode Island (Fig. 8) with some 6 m of soft unoxidized Coode Island Silt resting on compacted, oxidized Fishermens Bend Silt; the former has little bearing strength, while the latter offers a good foundation. Both formations are marine silts (as the fossils prove) laid down during an advance of the sea, but during the Last Glacial low sealevel, the Fishermens Bend Silt was drained, compacted and oxidized. Thus retreat of the sea resulted in a formation like the present marine muds of the Coode Island Silt (both contain *Anadara*) being transformed into a rock suitable for foundations. As the latter is so fine a sediment it could only be laid down more or less horizontally in conditions of low dynamics. The valleys in it were cut by subaerial erosion during the last low sealevel.

On the opposite side of Hobson Bay from Port Melbourne are Breakwater Pier and Gellibrand Pier. The distance they extended into the bay was determined by a deep channel cut during the last low sealevel and now infilled with soft silt without bearing-strength sufficient to support a pier. With ever larger oil tankers coming to Melbourne, it was necessary to extend Breakwater Pier, and the problem was solved by dredging to 18 m, then infilling with gravelly sand excavated from the bay floor off Middle Park. By courtesy of the Melbourne Harbor Trust Commissioners I saw the bores put down, and went on board the *A. D. McKenzie* during the dredging to examine the sediments brought up in the buckets (November 1953). A sample from 19 m below LWL (about the level of the Spencer St. stump and bog moss) was examined by the late Mr. N. B. Tindale, who determined the diatom flora, and found it comparable with a present-day flora from Hobart. The mollusc *Anadara trapezia* is characteristic of warmer waters further north, and is often known as the Sydney cockle. There it is common between tidemarks, but in Melbourne is at the extreme of its range, and generally is found only about LWL or below, where it is protected from the frost. This bivalve did not occur in the lower levels dredged, but was present in great numbers in the top of the section. There is thus some evidence of rising temperatures through the deposits of this channel, which is what one would expect on the glacio-eustatic principle but not if the structure were due simply to faulting.

The foregoing sites may now be compared with that at the new Art Gallery site in St. Kilda Road, S. Melbourne. Fig. 9 shows a section, and Fig. 10 the contours of the Silurian bedrock. By the courtesy of Sir Roy Grounds and Milton Johnson & Associates I was provided with bore logs and given access to the bore samples. It is observed that:

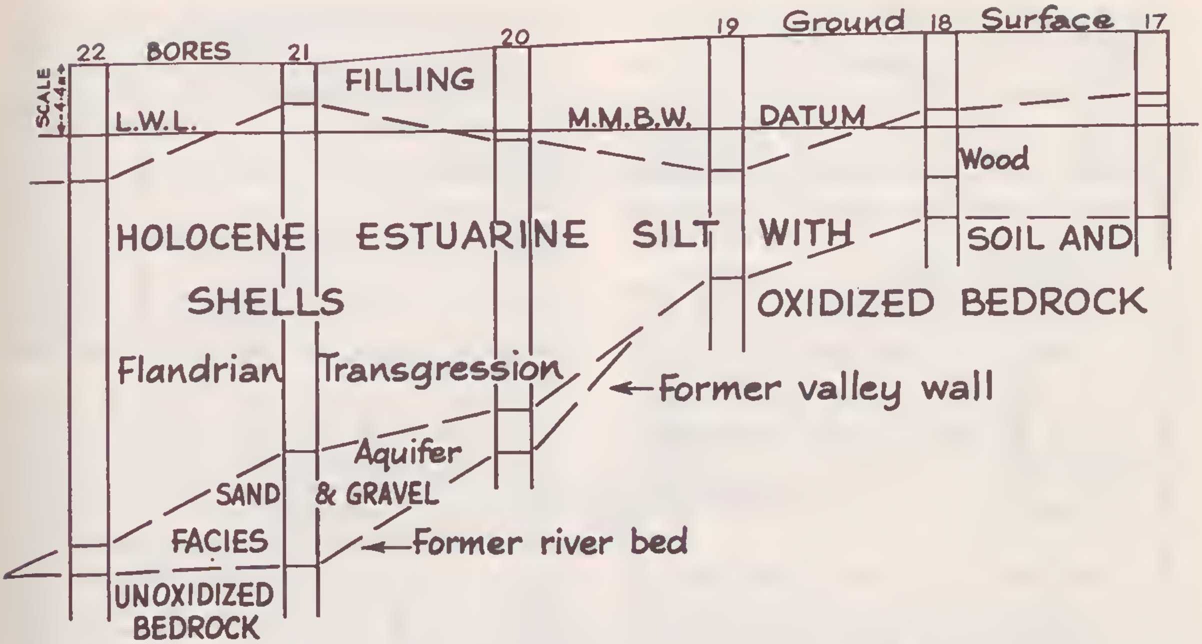

FIG. 9—Section through Art Gallery site, Melbourne (near SW. corner of Princes Bridge), showing a Last Glacial valley cut far below present sealevel, and infilled with Flandrian sediments.

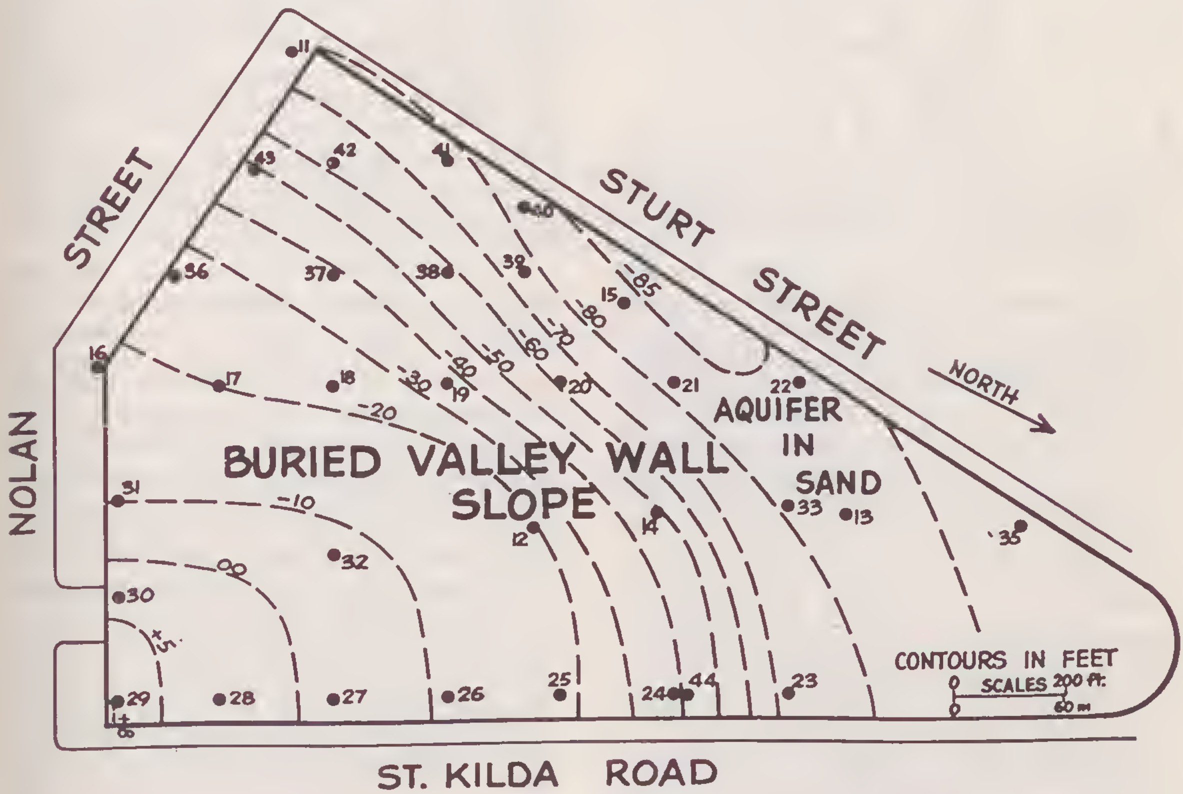

FIG. 10—Subsurface contours of the Silurian bedrock at the Art Gallery site, Melbourne, showing the E. wall of a Last Glacial Period valley, based on draft by Milton, Johnson & Associates.

(a) A channel 30 m from the surface and 25 m below LWL has been cut by the River Yarra.

(b) Wood was encountered in Bore 23 at 32 m from the surface in the Silurian bedrock, so presumably this consists of roots. I collected eucalypt roots under basalt in the floor of the Brooklyn deep sewer shaft over 30 m from the surface. Both occurrences indicate the presence of trees growing in the floor of the valley, which means that freshwater conditions prevailed.

(c) The Silurian bedrock is unoxidized below 25 m. Above this level the rock is oxidized wherever penetrated by bores. At the period when the bores were sunk, water stood near the present surface, so conditions must have been very different when air reached these rocks to oxidize them. It probably occurred during the low sealevel(s). The yellow clay with pieces of rock just above the Silurian is interpreted as a fossil soil with hillside talus.

(d) The buried valley has a steep SE. wall. This is true of the left bank of the present Yarra River as far as Merri Creek where the basalt begins. Because the basalt filled the old valley, the new Yarra River cut down steeply at the interface between the basalt and the bedrock (Fig. 5), forming cliffs in the latter as at Studley Park, E. of Melbourne city. During low sealevel(s) the river cut down further at the basalt/Silurian junction and so formed this steep valley wall.

(e) Changing ecology is indicated by the changing facies of the sediments that infill this old channel. At the base there is a gravel facies in the floor of the valley, followed by a sandy facies 4·5-6 m thick. This is an aquifer, and contained natural gas under pressure. Above is the main formation in the silt facies, a marine bed laid down as the sea returned from the Last Glacial low. Marine shells have been found in the bores and in excavations, proving that the sea deposited this formation. The three formations grade into one another, and constitute a single depositional series, but there is an obvious change in dynamics. When sealevel was low, the river flowed freely carrying gravel and sand. As the sea encroached again, a stillwater facies developed, and silts were laid in place of sands.

(f) Rocks that are absent are quite as signficant as those that are present. Firstly, no Last Interglacial yellow compacted silt (Fishermens Bend Silt) is present, so either this formation was never present, or (more likely) has been eroded away. It would have been welcome to provide a foundation nearer the surface. Secondly, no basalt flow (also a good foundation) is present. Basalt was reported in the vicinity of sealevel in bores 24 and 25, but probably only boulders are there because of the small thickness penetrated (0·3 m), the fact that bore 44 alongside bore 24 found none, and the general distribution of this rock.

(g) When the course of the ancestral River Yarra was filled by lava, the river re-established itself on the left bank at the edge of the basalt. During low sealevels a channel was excavated far below present sealevel along this edge, so that (Gill 1949) at Punt Rd. the bedrock is 18 m below sealevel, at Swan St. 19 m, at Russell St. 21 m, and at the Art Gallery site 25 m. So the Art Gallery site is in sequence, and probably represents a loop of the Yarra River formed during low sealevel.

(h) The Yarra River cut down to 25 m at the Art Gallery site (Last Glacial), and to 46 m on the W. side of the delta as is shown by the Lower Yarra Crossing bores (Penultimate Glacial). During the Last Interglacial, when sealevel was of the order of 7·5 m higher than now, marine beds were deposited and also river terraces in the coastal valleys were graded to this level. Dunes were stranded as the sea retreated. Queenscliff stands on part of such a dune line, and the Nepean Bay Bar (Keble 1946) across the mouth of Port Phillip Bay is the remnant of another. Since then sedimentation has occurred in Port Phillip, infilling the old channels. The lowering of sealevel by 46 m would join Flinders Is. on to Tasmania (Jennings 1959), and unite the islands of the Kent Group, and of the Hogan Group, between there and Victoria. A lowering of 64 m would provide a good land bridge between Victorian and Tasmania. Across such a land bridge the Tasmanian Aborigines no doubt crossed from the mainland to the island on which they were discovered.

(i) The chronology of the recent delta fill is provided by radiocarbon datings (Gill 1971). A sample of red gum from 28·4-28·7 m in Bore 10 of the King Street Bridge series (Duigan and Cookson 1957) gave a date 12,810 y. BP., while a similar sample from 19 m in Bore 23 of the Art Gallery series gave a date of 9,650 y. BP. The peat moss at Spencer St. bridge at about 19 m dated 8,330 y., while drift wood (accompanied by estuarine shells) at Power St., South Melbourne, not far from the Art Gallery, dated 6,010 y. BP. The youngest marine bed in the delta so far dated was that on the left bank of the Maribyrnong R. at the end of Brunel St., Essendon, viz. 4,820 y. (wood bored by marine borers and in a stratified bed of estuarine shells). This layer was 0·7 m above LWL, Hobson Bay. Similar shellbeds reach up the Yarra at least as far as the Church St. bridge. These figures suggest a mean depositional rate of 1 m per 290 y. (1 cm per 2·9 y.).

These observations on the geology of the Yarra

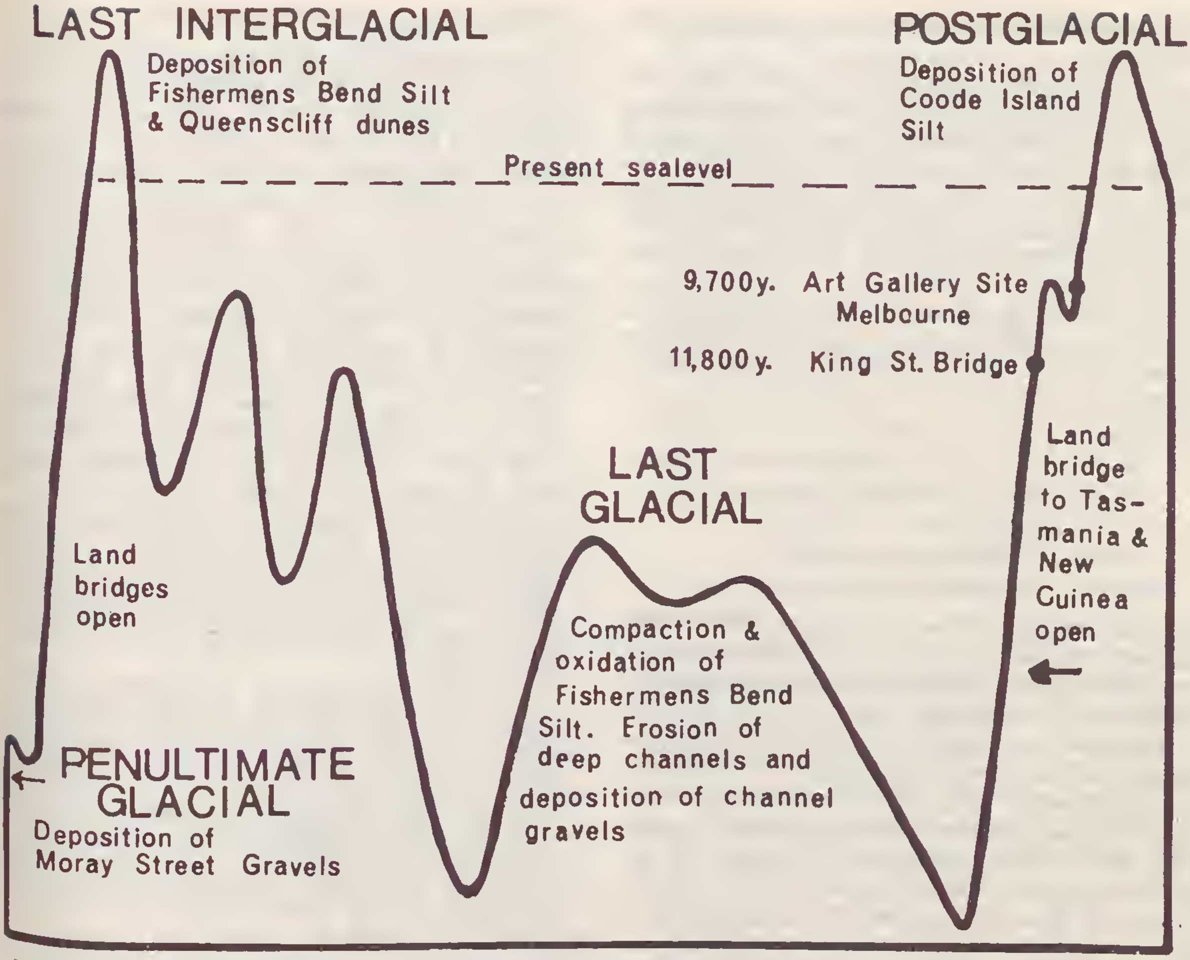

FIG. 11—Emiliani's palaeotemperature curve, which approximates the sealevel curve, because the latter is glacio-eustatic. Added are the geological formations of the Yarra Delta, Melbourne, showing their relationships to sealevel changes.

delta in relation to sealevel changes are summarized in Fig. 11.

EUSTASY AND TECTONICS

In 1948 ANZAAS set up a Quaternary Shorelines Committee to co-ordinate by discussion and report the research in Australia and New Zealand on sealevel changes, and to link this research with overseas efforts. At that time, there was a tendency to place tectonics and eustasy in apposition. Increased knowledge and a more quantitative approach has made it clear that (1) eustasy is a global phenomenon, affecting all coasts, and (2) no coast is completely stable, but there is an enormous range in the degree of stability. The best approach is to ask, if for a given period of time, the coast being studied has been stable within a named accuracy of measurement.

The evidence advanced earlier concerning the Yarra delta proves changed relationships between land and sea. If these changes were a function of tectonics alone, then in the past 30,000 years or so, the area has been lifted about 30 m to produce excavation of the channels, then dropped about 33 m to produce the postglacial flooding of the delta, and then raised 3 m in the last few thousand years to produce the emergence of the top of the Coode Island Silt. This is untenable because:

1. The rate of movement is out of character with the mild tectonics of the area. A tectonic environment like that in New Guinea would be needed.

2. The sudden reversals of direction in such brief time defy adequate explanation in an area of mild tectonics.

3. The low sealevels synchronize with the advance of the ice caps, while the high sealevels synchronize with their melting, thus favouring a glacio-eustatic explanation.

4. The curve of sealevel change is closely com-

parable with that observed widely throughout the world.

However, this does not mean that there has been no change in the level of the thick sediments since they were deposited. Compaction has caused lowering of levels. Also because the Yarra delta is in a sunkland setting, there probably has been a slight downward flexure, although this so far has defied measurement for the period of earth history involved.

At Altona on the west shore of Port Phillip bores and shafts sunk in connection with the winning of brown coal proved (e.g. 1928 No. 1 bore):

metres	
0 - 53	*Late Cainozoic basalt*
53 - 87	*Upper Cainozoic non-marine clayey sands*
87-108	*Miocene marine marl*
108-145	*Oligocene brown coal and clay.*

The surface at Bore 1 is about 15 m above present sealevel. Gradual sinking caused the accumulation of the thick brown coal and associated sediments. Continuation of this sinking admitted the Miocene sea. Sinking in Port Phillip has continued so that a considerable thickness of Pliocene and Pleistocene rocks occurs in the zone of maximum sinking. Altona is on a hinge area and so has not suffered maximum movement. If the commencement of the Oligocene (4×10^7 y) is taken as the beginning of accumulation, and if sealevel is taken as constant, then the land has sunk of the order of 130 m in 40,000,000 years, which is 1 cm in 3,077 y. If, because of the variables involved, we doubled or even trebled this figure, the movement is still very slow, and not significant for late Quaternary stratigraphy.

At Altona (Fig. 2) there are emerged Holocene shellbeds overlying the basalt where it is near sealevel. Hills (1940) has described this coquina as rising to 1·1 m above HWM. The tidal range is about 0·9 m (Bradley 1949). The shellbeds thus occur to 2 m above LWM. As these beds are of the order of 3 m thick where studied, the compaction factor is small. Any compaction that has occurred would mean that the sediments were deposited to that much higher above sealevel. Because of the nature of the stratification, this shellbed was deposited below low water mark, and if its position to 2 m above LWL is due to tectonic movement, then (a) the movement has been in the opposite direction from that inferred from stratigraphic evidence, and (b) the rate of movement is some 70 times faster than the mean rate calculated from the stratigraphy.

SEALEVELS AND ECOLOGY

The Altona shellbed has been explained (e.g. Jutson 1931) as due to high tides and storms, but this is unacceptable, for the shells are not broken and mixed up with other debris but are commonly whole, and quite often with both valves together in well stratified beds. The ecology is stillwater marine. Pritchard (1909) considered the formation was due to aggradation—forming a barrier then filling in behind it. This is similarly unacceptable on ecological grounds. Another explanation is that these beds represent former submarine banks (Hills 1940), but the fauna includes swamp, spray zone and intertidal shells; both sand and rock facies are represented. Such could easily accumulate in an area of shallow water deposition, but could not be lifted on to banks (if they existed) in a stillwater marine environment. In any case, such banks would be destroyed when passing through the surf zone unless elevation occurred in one climactic event, which could be out of character with the tectonics of the area.

The general structure of the Holocene beds at Altona is a stillwater marine stratum covered by a series of sandy beach ridges—an arrangement frequently found on the coasts of SE. Australia; it would seem that depressed ridges have been taken for submarine banks. In a culvert excavation on Miller Road, Altona, at the outlet to Lake Seaholme, the following section has been noted (Gill 1962, 1964):

THICKNESS	SEDIMENT	FACIES
metres		
0·0-0·6	*Black carbonaceous muddy sand*	*Marshland*
0·6-1·2	*Fawn sand (mottled with iron stains)*	*Beach*
1·2-1·6	*Fawn-grey coquina; paired whitish valves of mollusca not uncommon; top of bed sandy with mud content increasing to base*	*Stillwater Marine*
1·6-2·0	*Black sticky mud with marine fossils including paired valves of* Anadara trapezia	*Muddy inlet*
2·0-2·5+	*Bluish mud, firm but not sticky as bed above*	*Marshland*

Shells of *Katelysia rhytiphora* from the coquina gave a radiocarbon date of 5,560 ± 80 y. (NZ), while wood from a lower level dated 7,040 y. (GaK-1061). These beds grade into one another and form a sedimentary series without stratigraphic breaks. They define an advance, then retreat, of the sea, viz. marshland (as now), marine mud grading into marine sand (a rise in dynamics), then a stranded sandy beach and so back to the present marshland. The emergence is of the same amount and same time as found in numerous places along the coast of Victoria (Gill and Hopley 1971).

Further ecological information could be obtained by granulometric assay of the sediments, by chemical assay and by a faunal and floral assay covering the marine organisms, the spores and pollens, and the diatoms (which are good ecological indicators).

EUSTASY AND CYCLES OF SEDIMENTATION

The Altona site shows a cycle of marine advance beginning over 7,000 y. ago followed by a marine recession less than 5,500 y. ago. Another site providing evidence of postglacial changing relationships of land and sea is that at Seaspray on the Ninety Mile Beach, E. Victoria. The site was chosen because of (1) an extensive occurrence of emerged shellbeds, (2) the ecological contrast between a high energy open ocean beach and a still water facies behind the shoreline sand barrier, and (3) the extended section from the present shore to the postglacial cliff 1·6 km inland. A series of eight bores was planned to explore this section, the first being through the beach, the second through the barrier, and the rest at intervals through the alluvial flats between the barrier and the fossil cliff. Through the helpful co-operation of Dr. G. D. Aitchison, Chief, CSIRO Division of Applied Geomechanics, some of these projected bores (2, 4, 6, 8) were carefully sunk, undisturbed cores being taken (Gill 1970).

The village of Seaspray is on Merrimans Creek, S. of Sale. A large lagoon has been formed by a coastal barrier interfering with drainage to the sea. Behind this barrier are extensive flats extending for many miles parallel to the coast. On the inland edge of the flats is a former sea cliff. To overcome the drainage problems of these flats a large drain was cut from Merrimans Creek at Seaspray 3·2 km to Lake Reeve, a part of the Gippsland Lakes complex. This excavation revealed rich shellbeds extending over the whole distance. The facies is stillwater marine and there are variations from sandy mud to muddy sand. An auger hole was put down 664 m E. of the road on the E. side of Seaspray which proved the following stratigraphy:

metres	
0·0-0·6	*Black peaty soil*
0·6-0·7	*Grey sand*
0·7-1·8+	*Shell bed.*

A survey was made from this point to the beach, as shown in Fig. 12. It is difficult to measure sealevel on an open ocean beach, but from the above survey it was determined that the top of the coquina is of the order of 2·1 m above LWL. A temporary gauge will give a more reliable measurement. The tidal range along the Ninety Mile Beach is of the order of 2·4 m. *Anadara trapezia* shells were collected from muddy sediment at the top of the shellbed. Both valves were in place, and the shells appeared to be in position of life. Radiocarbon date for these shlls was 4,510 ± 80 y. (Gill 1971).

Excavations immediately behind the barrier showed that the upper shellbed extends to near the dune without change. Bore 2 shows that the lower shellbed passes below the barrier. Apparatus for boring beach sands was not available at the

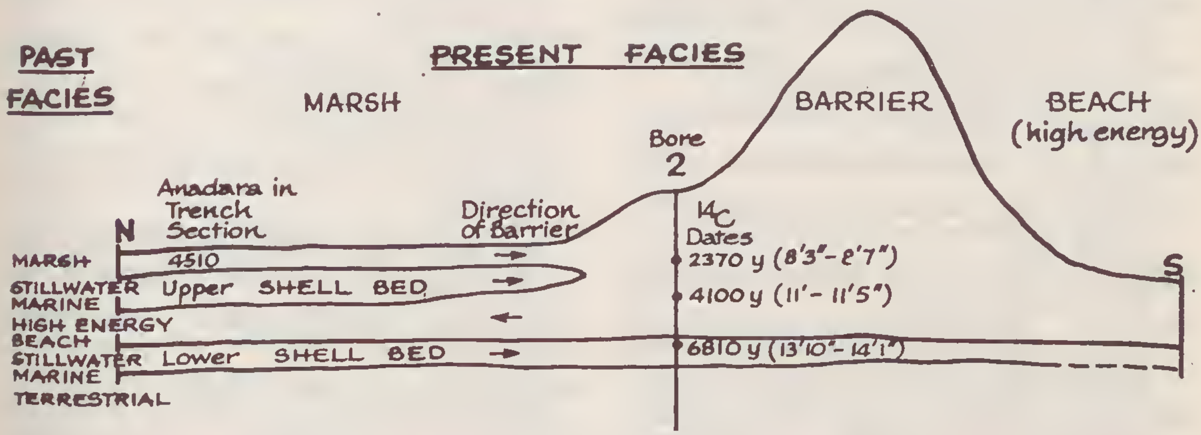

FIG. 12—Diagrammatic section through the shore and adjacent swampland N.E. of Seaspray, Gippsland, E. Victoria.

time of the field work to determine whether the shellbed passes under the beach, but fossil shells washed up on the beach support this interpretation. The barrier must have migrated over the shellbed as changes in sealevel shifted the shoreline. Since the Seaspray shellbeds are of stillwater marine facies, although beside an open ocean, there must have been a protecting barrier when they were laid down. As the shellbeds extend out towards the sea under the present barrier, it must once have been further seaward than at present.

EUSTASY AND THE FUTURE

Sealevel has been at a comparative stillstand over the past 6,000 y., which covers the time during which mensuration was evolved and used. During the Flandrian Transgression (*c.* 18,000-6,000 y. BP) the sea rose about 186 m in 12,000 y., a mean rate of 1·5 m per century. If such rapid change of sealevel began now, and the move were upwards, then within a century most wharves would be of limited use, some coastal towns would be drowned, the size of the Netherlands would be considerably reduced, and Venice would be lost. The mobility of sealevel in the past should lead us to expect that the present stillstand will not last a great deal longer. If, however, the next rapid sealevel movement is downward, then the problems of Venice, the Netherlands, and coastal preservation in general will be solved, but many wharf installations will be outmoded and many coastal holiday resorts lost. Modern man has not lived in a period of rapid sealevel change, and I believe that we should give more thought to this inevitable future event.

REFERENCES

Adams, R., 1865. Yarra floods and their remedy. *Trans. Proc. R. Soc. Vict.* 6: 148-155.

Aitchison, G. D. & Lang, J. G., 1962. Soil sampling for a river crossing investigation. *Proc. Aust. Rd Res. Bd* 1: 1213-1224.

Bell, G. *et al.*, 1967. Geology of the Melbourne district, Victoria. *Geol. Surv. Vict. Bull.* 59.

Bradley, J. E., 1949. Tides of Hobson Bay. *Proc. R. Soc. Vict.* 61: 113-122.

Bunce, D., 1857. *Australasiatic reminiscences.* 216 pp. Melbourne.

Chapman, W. D., 1929. Spencer St. bridge 1. Subaqueous foundation work. *J. Inst. Eng. Aust.* 1 (6): 211-220.

Darwin, F., 1887. *The life and letters of Charles Darwin.* 3 vols. London.

Dill, R. F., 1968. Deeply submerged terraces and low sea cliffs on the continental slope of Southern California, Baja California, Mexico, and Australia. *Geol. Soc. Amer. Progr. Abstr.* 1968, pp. 75-76.

Donald, I. B. & Ellwood, R. B., 1962. Geotechnical investigations for the proposed road crossing of the Lower Yarra River, Melbourne. *Proc. Aust. Rd Res. Bd* 1: 1173-1212.

Duigan, S. L. & Cookson, I. C., 1957. The occurrence of *Azolla filiculoides* L. and associated vascular plants in a Quaternary deposit in Melbourne, Australia. *Proc. R. Soc. Vict.* 69: 5-13.

Edwards, A. B., 1941. The north-west coast of Tasmania. *Ibid.* 53: 233-267.

Emery, K. O. & Milliman, J. D., 1971. Quaternary sediments of the Atlantic continental shelf of the United States. UNESCO Symposium. *Quaternaria*, in press.

Emery, K. O., Wigley, R. L., Bartlett, A. S., Rubin, M. & Barghoorn, E. S., 1967. Freshwater peats on the continental shelf. *Science* 158: 1301-1307.

Etheridge, R., David, T. W. E. & Grimshaw, J. W., 1897. On the occurrence of a submerged forest, with remains of the dugong at Sheas Creek, near Sydney. *J. R. Soc. N.S.W.* 30: 158-185.

Fairbridge, R. W., 1961. Eustatic changes in sea level. In Ahrens, R. L. *et al. Physics and Chemistry of the Earth*, New York, vol. 4: 99-185.

Flint, R. F. (In press). Presidential address to INQUA, Paris 1969.

Gill, E. D., 1949. The physiography and palaeogeography of the River Yarra, Victoria. *Mem. nat. Mus. Melb.* 16: 21-49.

————, 1955. Fossil insects, centipede and spider. *Vict. Naturalist* 72: 87-92.

————, 1961. Eustasy and the Yarra Delta, Victoria, Australia. *Proc. R. Soc. Vict.* 74: 125-133.

————, 1962. ANZAAS Committee for Investigation of Quaternary Strandline Changes: Report for Victoria. *Aust. J. Sci.* 25: 203-204.

————, 1964. Quaternary shorelines in Australia. *Ibid.* 26: 388-391.

————, 1967. Further Australasian research on Quaternary Shorelines. *Ibid.* 30: 15-18.

————, 1968. Eustasy. In *The Encyclopedia of Geomorphology* (Ed. R. W. Fairbridge). New York.

————, 1970. Current Quaternary shorelines research in Australasia. *Aust. J. Sci.* 32: 426-430.

————, 1971. Applications of radiocarbon dating in Victoria, Australia. *Proc. R. Soc. Vict.* 84: 71-85.

Gill, E. D. & Hopley, D., 1971. Holocene sea levels in eastern Australia. *Mar. Geol.* In press.

Hills, E. S., 1940. The question of recent emergence of the shores of Port Phillip Bay. *Proc. R. Soc. Vict.* 52: 84-105.

Huxley, J., 1957. The three types of evolutionary process. *Nature* 180: 454-455.

Jelgersma, S., 1966. Sea-level changes during the last 10,000 years. *R. met. Soc. Proc. internat. Symp. World Climate*, pp. 54-71.

Jennings, J. N., 1959. The submarine topography of Bass Strait. *Proc. R. Soc. Vict.* 71: 49-72, 71 (2) addendum.

Jutson, J. T., 1931. Erosion and sedimentation in Port Phillip Bay, Victoria, and their bearing on the theory of a recent relative uplift of the sea floor. *Ibid.* 53: 130-153.

Keble, R. A., 1946. The sunklands of Port Phillip Bay and Bass Strait. *Mem. nat. Mus. Vict.* 14 (2): 69-122.

Maxwell, W. G. H., 1968. Relict sediments, Queensland continental shelf. *Aust. J. Sci.* 31: 85-86.

Milliman, J. D. & Emery, K. O., 1968. Sealevels during the past 35,000 years. *Science* 162: 1121-1123.

NEILSON, J. L. & JENKIN, J. J., 1967. *Quaternary*. In BELL *et al.* 1967.

O'CONNELL, D. P., 1970. Marine resources and the law. *Aust. Acad. Sci. Symp. mar. Sci. Rept. Aust. Acad. Sci.* 12: 51-63.

PRITCHARD, G. B., 1909. The Recent shell-beds of Williamstown. *Vict. Naturalist* 26: 20-24.

RAWLINSON, Y. E., 1865. Notes on the tidal phenomena of Hobson's Bay, as affecting the discharge of flood waters from the River Yarra. *Trans. Proc. R. Soc. Vict.* 6: 161-167.

SCHOLL, D. W. & STUIVER, M., 1967. Recent submergence of southern Florida: a comparison with adjacent coasts and other eustatic data. *Bull. geol. Soc. Amer.* 78: 437-454.

SELWYN, A. R. C., 1868. *A descriptive catalogue of the rock specimens and minerals of the National Museum*. Govt. Printer, Melbourne.

SMITH, A. K., 1865. On the surface and underground drainage of the City of Melbourne. *Trans. Proc. R. Soc. Vict.* 6: 122-123.

———, 1874. On the prevention of street floods in the City of Melbourne. *Ibid.* 11: 1-8.

SUGGATE, R. P., 1968. Postglacial sealevel rise in the Christchurch metropolitan area, New Zealand. *Geol. Mijn.* 291-297.